Surprise For Science, Resilience For Ecosystems, and Incentives for People

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Ecological Applications, 6(3), 1996, pp. 733–735

SURPRISE FOR SCIENCE, RESILIENCE FOR ECOSYSTEMS, AND INCENTIVES FOR PEOPLE[1,2]

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It is an open question whether ecosystem management will become a passing fad, an expansion of existing rigid bureaucratic procedures, or a sustaining foundation for learning to deal with the interactions between people, nature, and economic activities. The report of the Ecological Society of America Committee on the Scientific Basis for Ecosystem Management makes a major contribution to the very best of those possibilities. Here I will comment on three consequences that flow from their conclusions—consequences for the kind of science, theory, and practice needed.

THE PROPERTIES OF ECOSYSTEMS

The accumulated body of empirical evidence concerning natural, disturbed, and managed terrestrial and nearshore ecosystems (Holling et al. 1995) identifies four key features of ecosystem structure and function that are consistent with the Ecological Society of America committee report on ecosystem management.

- Ecological change is not continuous and gradual. Rather it is episodic, with slow accumulation of natural capital such as biomass or nutrients, punctuated by sudden releases and reorganization of that capital as the result of internal or external natural processes or of man-imposed disturbances. That cycle functions at each of a number of scales—small and fast ones involving plant and soil processes of physiological ecology, through slower patch dynamics controlled by plant competition, through still coarser and slower ecosystems dynamics controlled by mesoscale processes like fire and human harvesting, to topographic properties shaped by geomorphological processes. Rare events, such as hurricanes, or the arrival of invading species, can unpredictably shape structure at critical times or at locations of increased vulnerability. The results of these rare events can persist for very long periods. That provides one of the sources of new options if existing diversity has not been compromised. Irreversible and slowly reversible states exist, i.e., once the system flips into such a state, only explicit management intervention can return its previous self-sustaining state, and even then success is not assured (Walker 1981). *Critical processes function at radically different rates covering several orders of magnitude, and these rates cluster around a few dominant frequencies* (Holling 1992).
- Spatial attributes are not uniform or scale invariant. Rather, productivity and textures are patchy and discontinuous at all scales from the leaf, to the individual, to the vegetation patch, to the landscape, and to the planet. There are several different ranges of scales each with different attributes of patchiness and texture and each is controlled by a different set of abiotic and biotic processes and variables. *Therefore scaling up from small to large cannot be a process of simple linear addition: nonlinear processes organize the shift from one range of scales to another. Not only does the large and slow control the small and fast, the latter occasionally "revolt" to affect the former as part of a natural process of renewal—witness insect outbreaks, fire, plant disease and large mammal herbivory* (Holling 1992).
- Ecosystems do not a have single equilibrium with functions controlled to remain near it. Rather, destabilizing forces far from equilibria, multiple equilibria, and absence of equilibria define functionally different states, and movement between states maintains structure and diversity. *On the one hand, destabilizing forces are important in maintaining diversity, resilience, and opportunity. On the other hand, stabilizing forces are important in maintaining productivity and biogeochemical cycles. Even when these features are perturbed, they recover rather rapidly if the stability domain is not exceeded* (e.g., recovery of lakes from eutrophication or acidification; Schindler 1990, Schindler et al. 1991).
- Policies and management that apply fixed rules for achieving constant yields (e.g., constant carrying capacity of cattle or wildlife, or constant sustainable yield of fish, wood, or water), independent of scale, lead to systems that gradually lose resilience, i.e., to ones that suddenly break down in the face of disturbances that previously could be absorbed (Holling 1986). *Ecosystems are moving targets, with multiple potential futures that are uncertain and unpredictable. Therefore management has to be flexible, adaptive, and experimental at scales compatible with the scales of critical ecosystem functions* (Walters 1986).

[1] Manuscript received 16 November 1995.
[2] For reprints of this Forum, see footnote 1, page 692.

KINDS OF SCIENCE

Those properties exaggerate the tensions between two streams of science—one reductionist and certain, one integrative and uncertain. The first stream is a science of parts, e.g., analysis of specific processes that affect specific variables—populations of individual species, levels of nutrients, flux of gases. It emerges from traditions of experimental science where a narrow enough focus is chosen in order to pose hypotheses, collect data, and design critical tests in order to reject invalid hypotheses. Since it is experimentally based, the scale chosen typically has to be small in space, the plot of a few square metres or the bagged small tree, and short in time, certainly not longer than the professional life of the experimenter or grant.

The goal of the science of parts is to narrow uncertainty to the point where acceptance of an argument among scientific peers is essentially unanimous. It is appropriately conservative and unambiguous, but it achieves that by being fragmentary and small in scale. It provides bricks for an edifice but not the architectural design.

The other is a science of the integration of parts. It uses the results of the first, but identifies gaps, develops alternative causative hypotheses, and constructs and uses models as devices for exploration and experimentation. The integrated consequence of each alternative hypothesis is evaluated by using information from planned and unplanned interventions in the whole system or by comparing and contrasting extreme examples. The goal is to narrow the range of possibilities by invalidating alternative hypotheses. The scales chosen are dictated by the question and not by practical limitations of experimentation.

This is a process of scientific inference, proceeding from simpler to more comprehensive representations in a series of steps. At each step conclusions are continuously challenged by posing and testing alternative explanations. Multiple lines of evidence are sought that progressively invalidate alternatives, leading to gradual convergence toward a credible line of argument. Typically, the goal is to reveal the simple causation that often underlies the complexity of time and space behavior of complex systems. There is a deep concern that a useful hypothesis might be rejected, i.e., concern more for Type II error (rejection of a true hypothesis) rather than only for Type I error (accepting a false hypothesis).

The premise of this second stream is that knowledge of the system we deal with is always incomplete. Surprise is inevitable. There will rarely be unanimity of agreement among peers, only an increasingly credible line of tested argument. Not only is the science incomplete, the system itself is a moving target, evolving because of the impacts of management and the progressive expansion of the scale of human influences on the planet.

Of course knowledge should be mobilized to reduce uncertainty where that is possible. But ecosystems and the human activities associated with them are inherently uncertain. Part of that is because of incomplete knowledge of novel interactions across space and time, and of novel relationships between nature and human behaviors. Part is because management changes the system being managed. Successfully managed systems are ever-changing targets because they release the resources for new kinds of human opportunity and they expose new classes of human risk.

In principle, therefore, there is an inherent unknowability, as well as unpredictability, concerning evolving managed ecosystems and the societies with which they are linked. There is an inherent unknowability and unpredictability to sustaining the foundations for functioning systems of people and nature. Inevitably information and decisions are vulnerable to being manipulated by powerful interests and the media. While scientists do not thereby become politicians, they do have to be sensitive to political and human realities. Recommendations have to be based on responsible judgment and interpretation of the burden of evidence. The Intergovernmental Panel on Climate Change is an effective, organized example of that process of accumulation of knowledge and its interpretation by scientists from a number of disciplines.

ECOSYSTEM MANAGEMENT PRACTICE

The remarks above emphasize that ecosystems are dynamic, inherently uncertain, with potential multiple futures. Moreover, managed ecosystems are transformed into new entities in order to create economic or social opportunity, and the success of that endeavor itself generates new classes of surprise and uncertainty. As a consequence, such evolving systems require policies and actions that not only satisfy social objectives but, at the same time, also achieve continually modified understanding of the evolving conditions and provide flexibility for adapting to surprises.

That is the heart of active regional experimentation by management at the scales appropriate to the question—adaptive environmental and resource management (Holling 1978, Walters 1986, Lee 1993). Otherwise the pathologies of either uncontrolled exploitive development or of command-and-control regulation are inevitable—increasingly brittle ecosystems, rigid management, and dependent societies leading to crises (Gunderson et al. 1995).

In adaptive management, policies are designed as hypotheses and management implemented as experiments to test those hypotheses. But the rule of good experimentation is that the consequences of the actions be potentially reversible and that the experimenter learns from the experiment. That requires ecosystems that are resilient and institutions that are flexible.

Resilience, as used here, is the ability of a system to absorb change and variation without flipping into a different state where the variables and processes controlling structure and behavior suddenly change (Holling 1973, 1995). Resilience therefore represents the property that sustains ecosystems. When it is lost, or when its limits are exceeded, unpredictability becomes dramatically increased and decision frustrated. But a necessary requirement for active adaptive experimentation is sufficient resilience to allow mistakes to occur. If that is not the case, then priorities for action must shift from active experimental manipulation to restoring resilience.

Institutions, as used here, are those sets of relationships that connect people to people and to nature. Flexible institutions are ones where signals of change are detected and reacted to as a self-correcting process and where knowledge and understanding accumulate—in short, where learning is possible in a changing world. If resilience represents the sustaining foundation for ecosystems, then useful and usable knowledge and the social trust to apply that knowledge represent the sustaining foundations for social development.

To conclude, the challenge is clear: With knowledge so dominated by understanding of small-scale processes, how can we evaluate the status of resilience in large ecosystems where mesoscale processes dominate—currents in oceans, migration of animals, large mammal herbivory, fires, insect outbreak, storm, and human land-use practices. What attributes of these processes and the patterns they produce can be manipulated to maintain or restore resilience? What incentives can be created for economic and private interests to maintain resilience when the signals of its importance only occur when it is too late? At the minimum, the goal for ecosystem management is understanding to reduce uncertainties, action to maintain or restore resilience, as insurance for the unknown, and creation of incentives for maintaining sustainable systems.

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